A SEARCH FOR CORE-COLLAPSE SUPERNOVA PROGENITORS IN *HUBBLE SPACE TELESCOPE* IMAGES[1]

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ABSTRACT

Identifying the massive progenitor stars that give rise to core-collapse supernovae (SNe) is one of the main pursuits of supernova and stellar evolution studies. Using ground-based images of recent, nearby SNe obtained primarily with the Katzman Automatic Imaging Telescope, astrometry from the Two Micron All Sky Survey, and archival images from the *Hubble Space Telescope*, we have attempted the direct identification of the progenitors of 16 Type II and Type Ib/c SNe. We may have identified the progenitors of the Type II SNe 1999br in NGC 4900, 1999ev in NGC 4274, and 2001du in NGC 1365 as supergiant stars with $M_V^0 \approx -6$ mag in all three cases. We may have also identified the progenitors of the Type Ib SNe 2001B in IC 391 and 2001is in NGC 1961 as very luminous supergiants with $M_V^0 \approx -8$ to -9 mag, and possibly the progenitor of the Type Ic SN 1999bu in NGC 3786 as a supergiant with $M_V^0 \approx -7.5$ mag. Additionally, we have recovered at late times SNe 1999dn in NGC 7714, 2000C in NGC 2415, and 2000ew in NGC 3810, although none of these had detectable progenitors on pre-supernova images. In fact, for the remaining SNe only limits can be placed on the absolute magnitude and color (when available) of the progenitor. The detected Type II progenitors and limits are consistent with red supergiants as progenitor stars, although possibly not as red as we had expected. Our results for the Type Ib/c SNe do not strongly constrain either Wolf-Rayet stars or massive interacting binary systems as progenitors.

Subject headings: supernovae: general — supernovae: individual (SN 1998Y, ...) — stars: massive — stars: evolution — stars: variables: other — galaxies: individual (IC 755, ...)

1. INTRODUCTION

Determining the progenitor stars that give rise to supernovae (SNe) is at the heart of SN research and is certainly a key aspect of stellar evolution studies. Without knowledge of the nature of SN progenitors, many of the conclusions and inferences that have been made from SNe on the chemical evolution of galaxies, the energy input into the interstellar medium, the production of stellar remnants such as neutron stars and black holes, the origin of cosmic rays, and even the determination of cosmological distances stand on precarious ground. The main obstacle is that a SN leaves few traces of the star that exploded. Additionally, only a small handful of the more than 2000 historical SNe have had pre-explosion objects identified. These include SN 1961V in NGC 1058 (Zwicky 1964, 1965), SN 1978K in NGC 1313 (Ryder et al. 1993), SN 1987A in the LMC (e.g., Gilmozzi et al. 1987; Sonneborn, Altner, & Kirshner 1987), SN 1993J in M81 (Aldering, Humphreys, & Richmond 1994; Cohen, Darling, & Porter 1995), and SN 1997bs in M66 (Van Dyk et al. 1999b, 2000). It should be noted that these five SNe were all at least somewhat unusual, and both SN 1961V (Goodrich et al. 1989; Filippenko et al. 1995; but see also Van Dyk, Filippenko, & Li 2002a) and SN 1997bs (Van Dyk et al. 2000) may not have been actual SNe (defined to be the catastrophic explosion of a star at the end of its life).

SNe are characterized optically by the presence or absence of H in their spectra near maximum brightness: the Type II SNe (SNe II) and Type I SNe (SNe I), respectively. SNe I further divide into SNe Ia, which are characterized by a deep absorption trough around 6150 Å produced by blueshifted Si II λ6355, and SNe Ib/c, which do not show this trough. SNe Ib exhibit strong He I absorption, while SNe Ic show little or no evidence for He I absorption. The SNe II also include various subtypes: SNe II-plateau (II-P) and II-linear (II-L), based on the shape of their light curves (but with associated spectral characteristics as well; Schlegel 1996; Filippenko 1997), and SNe II-narrow (IIn), which lack the blueshifted component of the broad Balmer-line P-Cygni profiles, but instead show a relatively narrow emission component atop the broad one. SNe IIb may be a bridge between the SNe II and Ib/c, possessing properties of each. (See Filippenko 1997 for a thorough review of SN spectra and types.)

SNe Ia are thought to arise from the thermonuclear deflagration and/or detonation of a white dwarf, but they are not the focus of this paper. SNe II and Ib/c probably arise from the collapse of the Fe core toward the end of the life of a massive ($M \gtrsim 10\ M_\odot$) star. Whereas it is generally agreed that SNe II must arise from the explosions of hydrogen-rich supergiant stars, the progenitors of SNe Ib/c have not been unambiguously identified. Clearly, SNe Ib/c must arise from stars that have lost most or all of their hydrogen envelopes. As such, Wolf-

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Rayet stars have been proposed as possible progenitors (see Branch, Nomoto, & Filippenko 1991, and references therein). Alternatively, Uomoto (1986), Nomoto, Filippenko, & Shigeyama (1990), Podsiadlowski, Joss, & Hsu (1992), Iwamoto et al. (1994), and Nomoto et al. (1996) have explored massive gas-transferring binary systems as possible SN Ib/c progenitors. (Another possibility, now considered much less likely, are off-center explosions of white dwarfs; Branch & Nomoto 1986.)

Part of the evidence for the core-collapse nature of SNe II and Ib/c comes from theoretical modelling (e.g., Woosley & Weaver 1986, 1995), but indications that these SNe have massive-star progenitors also stems from the few that have had progenitors directly identified: for SN 1961V, an extremely luminous ($M^0_{\rm pg} \approx -12$ mag) star (Bertola 1964; Zwicky 1964; Klemola 1986); for SN IIn 1978K, a reddish star, with $B-R \approx 2$ mag and $M_B \approx -6$ mag (Ryder et al. 1993); for SN II-P 1987A, a massive blue supergiant (e.g., Woosley 1988); for SN IIb 1993J, a red supergiant, possibly in a binary system (Podsiadlowski et al. 1993; Aldering et al. 1994; Van Dyk et al. 2002b); and for SN IIn 1997bs, a supergiant star with $M_V \approx -7.4$ mag (Van Dyk et al. 1999b, 2000). In addition, young SN remnants, such as Cas A (e.g., Fesen, Becker, & Blair 1987; Fesen & Becker 1991; García-Segura, Langer, & Mac Low 1996), clearly point toward massive progenitors.

Evidence for massive progenitors has also been accrued from the environmental data for many SNe. Van Dyk (1992) and Van Dyk, Hamuy, & Filippenko (1996) provided statistics of the association of SNe II and Ib/c with massive star-formation regions, from ground-based imaging. More recently, Barth et al. (1996) and Van Dyk et al. (1999a,b) have exploited the superior spatial resolution afforded by the *Hubble Space Telescope* (*HST*) to resolve individual stars in SN environments and place constraints on the progenitor ages and masses. Based on the properties of the surrounding stellar association, Van Dyk et al. (1999a), in particular, concluded that the progenitor of the SN II-L 1979C in M100 had an initial mass $M \approx 17$–$18\ M_\odot$. Using *HST* images of SN 1993J in M81 to remove contamination by neighboring stars of the ground-based estimates of the progenitor brightness (Aldering et al. 1994), Van Dyk et al. (2002b) constrain the progenitor mass to be $\sim$13–22 $M_\odot$.

Clearly, direct identification of the progenitors of additional core-collapse SNe is essential. Van Dyk et al. (1999b, 2000) were able to directly identify the progenitor star for SN 1997bs using *HST* archival images. However, at that point in time the quantity of archival data in which pre-SN images might exist for recent SNe was extremely small. We can now reap the benefits from the confluence of two circumstances: the increasing data volume in the *HST* archive and the success of modern SN search programs, in particular, the Lick Observatory SN Search (LOSS; Li et al. 1999; Filippenko et al. 2001) and the Lick Observatory and Tenagra Observatory SN Searches (LOTOSS; Schwartz et al. 2000; Beutler et al. 2002), with which two of us (W.D.L. & A.V.F.) are involved and which are discovering new SNe at a remarkable rate (e.g., 65 in 2002 January–September).

In this paper we discuss our attempt to isolate the progenitors of 16 core-collapse SNe (6 SNe II and 10 SNe Ib/c) using *HST* Wide Field Planetary Camera 2 (WFPC2) images of galaxies. It will only be through the accumulation of a statistically significant number of direct identifications of progenitor stars for both SNe Ib/c and SNe II that we finally will be able to adequately test the various models for massive stellar evolution and inevitable explosion.

2. METHOD OF ANALYSIS

We began by cross-referencing historical SNe with the *HST* archive. We compiled a list of core-collapse events, all since about 1997 through 2002 June, which might contain the progenitor star in at least one WFPC2 image. A summary of the available data is in Table 1. The crux of this work is determining at which location on the four chips of the image array the star should be. It is therefore of utmost importance to have high astrometric accuracy for all the images. Ideally, one could pinpoint the exact SN location by comparing a late-time image of the SN with a pre-SN image. In fact, in three cases below, we have been able to do this. However, even locating the fading SN in *HST* images is often quite difficult and requires high astrometric precision.

It is reasonably straightforward to measure accurate positions (to fractions of an arcsec) for SNe on high-quality ground-based images. However, it is well known that positions based on the astrometric information in the *HST* image headers alone are not very accurate. Online documentation[2] for WFPC2 claims an accuracy of $\sim 0''.5$; from experience, however, we have found it to be more typically $\sim 1''.5$ *or worse* (see, e.g., Filippenko et al. 1995; Van Dyk et al. 1999b). It is thus incumbent upon us to apply an *independent* astrometric grid to the WFPC2 images.

For this reason we have adopted the Two Micron All Sky Survey (2MASS) as the basis for the astrometric grid for both the ground-based SN images and the *HST* images potentially containing the SN progenitor. While it is well known that the 2MASS near-infrared catalogs are an unprecedented photometric resource, a less recognized fact is that the Point Source Catalog is also of outstanding astrometric quality, with residuals in the final Catalog typically and conservatively $0''.10$ (H. McCallon & R. Cutri 2002, private communication). The J-band 2MASS images correspond quite well with the optical SN and *HST* images, such that a sufficient number of astrometric fiducial stars on the optical images can be employed to achieve accuracies in the astrometric solutions of typically $0''.2$–$0''.3$. For WFPC2 this means, with a plate scale of $0''.1$ pixel^{-1}, that we can estimate the position of the progenitor star on a WF chip with uncertainty in the range of only three to nine pixels (roughly double this pixel range for the PC chip).

Unless otherwise specified, we have measured all of the SN positions from R-band or unfiltered images obtained by the Katzman Automatic Imaging Telescope (KAIT; Filippenko et al. 2001; KAIT is the principal instrument for LOSS/LOTOSS), as part of KAIT SN light-curve monitoring (see, e.g., Li et al. 2001; Modjaz et al. 2001b; Leonard et al. 2002a,b). We then use the STSDAS routine *wmosaic*

[2]http://www.stsci.edu/instruments/wfpc2/Wfpc2_faq/wfpc2_ast_faq.html.

within IRAF[3] to stitch together the four WFPC2 chips to obtain the full WFPC2 field of view. (This step is generally necessary for there to be enough available fiducial stars to facilitate the astrometry.) The *wmosaic* routine makes corrections for geometric distortion in each chip and for the rotation, offsets, and scale differences among the chips. Application of 2MASS to the full mosaic results in an astrometric reference frame, or grid, of satisfactorily high accuracy, verified by the resulting positions of at least one or more "check stars" on the mosaic. (The key, again, is that we are not employing the *HST* image header information, but imposing our own astrometric grid on the mosaic.)

Often we could match unsaturated stars on the WFPC2 mosaic with 2MASS sources and directly derive an astrometric solution for the mosaic. When this was not possible, owing to a lack of 2MASS sources seen on the WFPC2 mosaic, we matched 2MASS sources first with relatively bright (but unsaturated) stars on deep optical images (typically V band) of the SN host galaxies (obtained in 2002 February and April at the Palomar 1.5-m telescope) and then, once an astrometric solution had been obtained, matched fainter stars seen in both the deep ground-based images and the WFPC2 mosaic, obtaining a new astrometric solution based on these objects. All astrometric solutions were derived throughout using the IRAF task *ccmap* and applied using *cctran*. Finally, we then determined the individual WFPC2 chip pixel value and the uncertainty in that value for the SN site and, therefore, for the progenitor.

Once the site was located, photometry of the appropriate WFPC2 chip was performed using the routine HSTphot (Dolphin 2000a,b), which automatically accounts for WFPC2 point-spread function (PSF) variations and charge-transfer effects across the chips, zeropoints, aperture corrections, etc., and can return magnitudes in standard Johnson-Cousins bands as output, whenever possible. HSTphot was run in all cases with a 3σ detection threshold. Dolphin (2000a) tested HSTphot against DoPHOT on the same dataset and found no systematic differences in the results from the two packages. Similarly, Saha et al. (2001), in their measurement of the Cepheid distance to NGC 3982, find the HSTphot results to be within the errors of the DoPHOT results. Extensive tests by D. C. Leonard (2002, private communication) of DAOPHOT against HSTphot also show very good agreement (in particular, on images of NGC 3351, he finds $\delta V = 0.016$ and $\delta I = 0.043$ mag; see Graham et al. 1997). Consequently, we can determine the magnitude and, when available, the color of the candidate progenitor, although, as we will see, for most objects this turns out to be placing only a *limit* on the magnitude and color.

In three cases we were able to recover the SN in a late-time image, allowing us to isolate the exact position of the progenitor. These detections serve as a valuable test of our method: if the astrometric grid is truly accurate, we should be able to locate the old SN in a straightforward manner, which, in fact, proves to be the case. We emphasize that, short of having an accurate absolute position for these SNe, the generally faint sources would be relatively difficult to unambiguously locate on a WFPC2 chip, especially with the possible presence of other variable stars in the host galaxy. The coincidence of the estimated SN position on the chip with the actual recovery position provides us with some confidence in the progenitor positions for the other cases, where no late-time image of the SN is available.

All quoted positions are J2000 throughout. All observing dates are in UT, and the relevant *HST* GO or GTO program is given in each case. Unless otherwise specified, the distance to the host galaxy is derived from the heliocentric radial velocity corrected for Local Group infall into the Virgo Cluster given in the Lyon-Meudon Extragalactic Database (LEDA), and is based on an assumed distance scale of 65 km s^{-1} Mpc^{-1}. For lack of other data, the extinction correction toward the SN is limited in most cases to the Galactic component [generally adopting A_V from the NASA/IPAC Extragalactic Database (NED), and originally from Schlegel, Finkbinder, & Davis (1998)], assuming the Cardelli, Clayton, & Mathis (1989) reddening law. All limiting magnitudes and colors, unless otherwise specified, are based on the 3σ detection limits. Below we discuss the individual core-collapse SNe and their possible progenitors.

3. THE SUPERNOVAE AND THEIR PROGENITORS

3.1. *SN 1999an in IC 755*

SN 1999an was discovered by Wei et al. (1999) as part of the Beijing Astronomical Observatory (BAO) SN Search and was classified as a SN II by Cao & Gu (1999). We measure the SN position from a KAIT image as $\alpha = 12^h01^m10\overset{s}{.}57$, $\delta = +14°06'11\overset{''}{.}1$, with uncertainty $\pm0\overset{''}{.}4$. The host galaxy was imaged in F606W (160 s) by GO-5446 on 1995 January 5. The Galactic foreground stars around the host on the WFPC2 mosaic are quite faint, and so we used a deep Palomar V-band image to establish the astrometric grid for the mosaic. The uncertainty in the positions for these stars in the Palomar image is $\pm0\overset{''}{.}2$. However, applying the grid to the mosaic resulted in an uncertainty of $\pm0\overset{''}{.}6$, likely due to the relative faintness of the stars in the mosaic. Together with the measured uncertainty in the SN position, this results in a total uncertainty of $\pm0\overset{''}{.}8$ in the SN position on the mosaic (the uncertainties in the measured SN position and in the astrometric grid were added in quadrature here and throughout).

Figure 1 shows the SN site on the WF2 chip. Within the error circle are six objects, with $m_{\rm F606W} \approx 21.9$–$22.9$ mag. However, HSTphot considers them all to be spatially extended (non-stellar). Assuming a host galaxy distance of 23 Mpc (based on Tully-Fisher estimates by Yasuda, Fukugita, & Okamura 1997) and Galactic $A_V = 0.1$ mag, these objects have $M_V^0 \approx -9.0$ to -10.0 mag, which are at the extreme end of observed stellar luminosity in the Milky Way (e.g., Humphreys & Davidson 1979). It is therefore likely that these are compact star clusters. The progenitor may have been a member of one of these clusters, and we are unable to resolve it. It is also possible that the progenitor was not a member and also not detected in the image. If the latter is the case, then from the detection limit in the SN environment ($m_{\rm F606W} \gtrsim 25.0$ mag) we can

[3]IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

place an upper limit on the progenitor's absolute visual magnitude of $M_V^0 \gtrsim -6.9$ mag.

3.2. *SN 1999br in NGC 4900*

SN 1999br was discovered by King (1999) as part of LOSS and was classified as a SN II by Garnavich et al. (1999a) and Filippenko, Stern, & Reuland (1999); the latter point out that the SN is very subluminous, regardless of its type. Patat et al. (1999) and Zampieri et al. (2002) conclude that a smaller than "normal" ^{56}Ni mass must have been produced in the explosion. Nonetheless, Hamuy & Pinto (2002) consider SN 1999br as a SN II-P. We measure the SN position from a KAIT image as $\alpha = 13^h00^m41\overset{s}{.}82$, $\delta = +02°29'45\overset{''}{.}4$, with uncertainty $\pm0\overset{''}{.}2$. The host galaxy was imaged in F606W (160 s) by GO-5446 on 1995 January 29. The stars useful for astrometry in the WFPC2 mosaic are all quite faint (the bright star near the SN position is saturated); therefore, we used a deep Palomar V-band image to establish the astrometric grid for the mosaic, with uncertainty $\pm0\overset{''}{.}3$, which results in a total uncertainty of $\pm0\overset{''}{.}5$.

Figure 2 shows the SN site on the WF3 chip. A very faint object is seen within the error circle, but it is not detected by HSTphot. A brighter object is detected along the north-northeast edge of the circle, with $m_{\rm F606W} = 24.96\pm0.27$ mag. Tentatively, we assign this as the possible progenitor of SN 1999br (it is detected in the F606W image at the 4σ level). The host galaxy has also been very recently (on 2002 June 20) and more deeply imaged by GO-9042 in F450W and F814W (460 s each). It is therefore possible that we can detect the SN at late times and pinpoint the exact progenitor location. We applied the same grid as on the F606W mosaic to the F450W and F814W mosaics, using four of the same five faint fiducial stars.

Figure 3 illustrates the SN site on the PC chip and also shows that the astrometry produces quite similar results as in Figure 2 for the SN location. However, no object is detected within the error circle to $B \gtrsim 25.3$ and $I \gtrsim 24.5$ mag. This is consistent with an extrapolation from the late-time SN photometry (SN 1999br was last detected in 2000 April at $B \approx 23.6$ and $I \approx 21.2$ mag, and, following the ^{56}Co decay rate, a decline of $\sim$8 mag is expected between 2000 April and 2002 June; A. Pastorello 2002, private communication). We therefore most likely have *not* recovered the SN in these 2002 images. However, the fact that the possible progenitor object identified above is no longer detected in the deep F450W and F814W images indicates that we may have identified the SN progenitor in the older (1995) F606W image.

For a distance of 17.3 Mpc (Ho, Filippenko, & Sargent 1997) and Galactic extinction toward the host galaxy $A_V = 0.08$ mag [Hamuy & Pinto (2002) list $A_V \approx 0$ mag within the host, based on the SN color at the end of the plateau], we find that $M_V^0 \approx -6.3$ mag for this star, consistent with that for late-type (M-type) supergiants (Humphreys & Davidson 1979). Unfortunately, no color information exists for this star. If it is not the progenitor, we can place a limit on the progenitor's absolute magnitude of $M_V^0 \gtrsim -5.9$ mag, based on the F606W image detection threshold ($m_{\rm F606W} \gtrsim 25.4$ mag).

3.3. *SN 1999bu in NGC 3786*

SN 1999bu was discovered by Li (1999) using KAIT, about 1$''$ W and 3$''$ S of the host galaxy nucleus. Jha et al. (1999a) classified it as a SN Ic. NGC 3786 was imaged by GO-5479 in a single 500-s F606W exposure on 1995 March 30. Only two stars are seen in the WFPC2 mosaic. For this reason, we performed an offset from a relatively bright (but unsaturated) star $11\overset{''}{.}96$ W and $11\overset{''}{.}90$ N of the SN site. This offset was determined from a KAIT image of the SN, after galaxy background light had been subtracted to make it easier to derive a centroid for the SN. We applied the same offset from this star on the WFPC2 mosaic, and we show the SN position on the PC chip in Figure 4. We have adopted an uncertainty in the offset which is the uncertainty in the astrometry of the KAIT image, namely $\pm0\overset{''}{.}5$.

Three objects are detected within and along the northern edge of the error circle. Object A is considered extended by HSTphot and has $m_{\rm F606W} = 23.62\pm0.01$ mag. Object B is also considered extended and has $m_{\rm F606W} = 23.54\pm0.01$ mag. Object C, just east of north along the circle edge, is considered stellar and has $m_{\rm F606W} = 25.72\pm0.31$ mag.

For a distance of about 42 Mpc [correcting the distance of 36.1 Mpc from Pogge & Martini (2002) to our assumed distance scale] and Galactic extinction $A_V = 0.08$ mag, objects A and B, presumably small star clusters, have $M_V^0 \approx -9.6$ and -9.7 mag, respectively, brighter than known supergiants. Object C, however, has $M_V^0 \approx -7.5$ mag, consistent with supergiant brightnesses; although it is at the edge of the error circle, it could possibly be the progenitor. Alternatively, the progenitor may have been a member of the two clusters and is unresolved. It is also possible that it was not object C and was not a cluster member, and was not detected. If the latter is the case, then from the detection limit in the SN environment ($m_{\rm F606W} \gtrsim 26.1$ mag), we estimate $M_V^0 \gtrsim -7.1$ mag for the progenitor.

3.4. *SN 1999bx in NGC 6745*

SN 1999bx was discovered using KAIT by Friedman & Li (1999). The host galaxy, NGC 6745 (UGC 11391), may actually be an interacting galaxy pair, and the SN occurred about 2$''$ W and 15$''$ N of the southern of the two nuclei. Jha et al. (1999b) classified it as a SN II. From a KAIT image, we measure the SN position as $\alpha = 19^h01^m41\overset{s}{.}39$, $\delta = +40°44'52\overset{''}{.}0$, with uncertainty $\pm0\overset{''}{.}2$. NGC 6745 was imaged very deeply in F336W (22000 s), F555W (4800 s), F675W (5200 s), and F814W (5200 s) on 1997 March 19 and 21 by GO-6276. Applying the 2MASS astrometric grid directly to the F555W mosaic, with total positional uncertainty $\pm0\overset{''}{.}4$, we show in Figure 5 the SN site on the WF3 chip.

We detect four objects (A–D) within, or along the edge of, the error circle, and with the good color coverage discussed above, we can derive useful information about them. HSTphot considers the two objects at the western circle edge, A and B, to be stellar, with $V = 24.37\pm0.09$ and 25.01 ± 0.20 mag, respectively, whereas the two eastern objects, C and D, are likely extended, with $V = 23.75\pm0.01$ and 23.53 ± 0.01 mag, respectively. Assuming a distance of about 74 Mpc and Galactic extinction

$A_V = 0.44$ mag, the two western objects, A and B, have $M_V = -10.4$ and -9.8 mag, respectively, certainly at the upper end of possible stellar luminosities, while the two eastern objects, C and D, have $M_V = -11.0$ and -11.3 mag, respectively, almost certainly too bright to be single stars. Additionally, Objects A and B are quite blue: for A, the reddening-corrected colors are $(U-V)^0 = -0.38$, $(V-R)^0 = 0.01$, $(R-I)^0 = 0.19$, and $(V-I)^0 = 0.20$ mag; and, for Object B, $(U-V)^0 = -0.56$, $(V-R)^0 = 0.60$, $(R-I)^0 = 0.20$, and $(V-I)^0 = 0.80$ mag. Colors for Object B indicate that it may be a composite of blue and red objects.

It is therefore likely that the detected objects are too luminous and too blue to be the possible progenitor of SN 1999bx, since as a SN II, we might expect the progenitor to have been a red supergiant. We cannot rule out that the progenitor was either an unresolved member of likely clusters C and D, or was blended with luminous stellar Objects A or B. However, if it is undetected, limits on the absolute magnitude and color of the progenitor are $M_V^0 \gtrsim -7.8$, $(U-V)^0 \lesssim 0.5$, $(V-R)^0 \lesssim 0.9$, $(R-I)^0 \lesssim 1.0$, and $(V-I)^0 \lesssim 1.6$ mag. (Color limits here and throughout are derived from the larger SN environment, $\sim 10''$ or so, depending on the image, and are not particularly restrictive.)

3.5. *SN 1999dn in NGC 7714*

SN 1999dn was discovered by Qiu et al. (1999) as part of the BAO SN Search. It was classified as a SN Ic by Ayani et al. (1999) and Turatto et al. (1999). Pastorello et al. (1999) describe the strong resemblance of SN 1999dn to SNe 1997X, 1994I, and 1996aq around maximum brightness, with He I lines detected; they argue that it should be considered as a SN Ib/c. Deng et al. (2000) and Matheson et al. (2001a) further refine the classification to Type Ib; Branch et al. (2002) consider it the currently best-observed, "fiducial" SN Ib. Deng et al. (2000) also find strong evidence for both Hα and C II $\lambda 6580$. They conclude that the low-mass H skin above the He layer in SN 1999dn makes this event a possible link between SNe Ib and IIb, such as SN 1993J (e.g., Filippenko, Matheson, & Ho 1993). From a KAIT image we measure the SN position as $\alpha = 23^h36^m14.^s81$, $\delta = +02°09'08.''4$, with uncertainty $\pm 0.''5$.

SN 1999dn is potentially one of the more interesting objects in this study, since we can attempt to detect the faint SN in one of our own *HST* Snapshot images (GO-8602; see Li et al. 2002, which does not include SN 1999dn in the analysis) and compare this with the pre-SN archive image. We obtained a 700-s F814W image (cosmic-ray split pair) on 2001 January 24, and 700-s splits each in F555W and F814W on 2001 July 10. However, this turned out to be one of the most difficult sets of *HST* images for which to establish an astrometric grid, due to the lack of stars in common between these images and 2MASS detections (unfortunately, we did not observe the host galaxy at Palomar). Nonetheless, we can apply a grid, with $\pm 0.''4$ uncertainty, and locate the SN on the PC chip for the first pair of F814W exposures from 2001 January, with total uncertainty $\pm 0.''6$. The SN is most likely the faint object just east of the error circle center in Figure 6 (we have applied the routine *qzap*, written by M. Dickinson, to the image in the figure, to remove residual cosmic-ray hits; the object to the south is seen at about the same brightness in the second F814W image pair from 2001 July). The SN had $m_{\rm F814W} = 24.18 \pm 0.18$ mag. It is undetected in either band of the second set of Snapshot images, to $V \gtrsim 26.2$, $V - I \lesssim 2.0$ mag. (Two 300-s F300W images were also obtained by GO-9124 on 2001 August 3, but the SN had most likely faded well below detection in these images, and so we do not further consider them.)

The site is also in a single 500-s F606W exposure obtained by GO-5479 on 1996 May 15 and in four F380W images (total exposure time 1800 s) obtained by GO-6672 on 1998 August 29. We show in Figure 7 the SN site in the F606W image (on the PC chip; again, we have applied *qzap* to make the image more cosmetically appealing in the figure). Nothing is detected at the SN site to $m_{\rm F606W} \gtrsim 26.0$ mag. Additionally, nothing is detected in the F380W image to $m_{\rm F380W} \gtrsim 24.7$ mag. For a distance of about 43 Mpc and Galactic $A_V = 0.17$ mag [Turatto et al. (1999) indicate no extinction to the SN], the corrected magnitude and color correspond to $M_V^0 \gtrsim -7.3$, $(U-V)^0 \lesssim 2.5$ mag for the progenitor.

3.6. *SN 1999ec in NGC 2207*

SN 1999ec was discovered using KAIT by Modjaz & Li (1999). The SN was classified as a SN Ib by Jha et al. (1999c), although Matheson et al. (2001a) consider it a peculiar SN I, without a well-defined type, similar to SN 1993R (cf. Filippenko & Matheson 1993). We measure on a KAIT image the SN position as $\alpha = 06^h16^m16.^s18$, $\delta = -21°22'10.''1$, with uncertainty $\pm 0.''2$. [This position is discrepant by at least $1''$ with that referred to by Elmegreen et al. (2001).] The host galaxy is part of an interacting system, extensively studied by Elmegreen et al. with *HST* (GO-6483); only their "NGC2207-NW" F336W (2000 s), F439W (2000 s), F555W (660 s), and F814W (720 s) images from 1996 May 25 are of use here. We apply the 2MASS astrometric grid directly to the WFPC2 F555W mosaic, with uncertainty $\pm 0.''2$. Figure 8 shows the SN site on the F555W WF2 chip, with total uncertainty $\pm 0.''3$.

A hint of an object is possibly seen within the circle, but nothing is detected there by HSTphot to $V \gtrsim 25.9$ mag. The Galactic extinction is $A_V = 0.29$ mag. To derive possibly more accurate limits on the brightness and color of a progenitor star, we exploit the color information available to us for objects in the SN's environment, to possibly estimate the local extinction. As can be seen from the color-color diagram in Figure 9, HSTphot considers most of the objects around the error circle to be extended; they are likely star clusters. However, two objects are considered stellar, and the one (Star 1) closest to the SN position implies that $A_V \approx 1.6$ mag (though the U-band photometry may be the least certain, the extinction, even for the clusters, appears to range from ~ 1 to ~ 3 mag). Although it is at the edge of the error circle, it is possible that Star 1, with $V = 23.42$, $U - B = -0.92$, $B - V = 0.43$, and $V - I = 0.38$ mag, is the progenitor. Adjusting the distance to the host from Elmegreen et al. (2001) to about 40 Mpc for our adopted distance scale, and assuming the A_V derived from Star 1, this leads to the star having a very blue intrinsic color [$(U-B)^0 = -1.3$, $(B-V)^0 = -0.1$, and $(V-I)^0 = -0.2$ mag], but also $M_V^0 \approx -11.2$ mag, which is likely too high for known stars. If Star 1 is not the progenitor, which we consider more likely, then $M_V^0 \gtrsim -8.7$, $(U-B)^0 \lesssim -0.3$, $(B-V)^0 \lesssim 0.2$, and $(V-I)^0 \lesssim 0.9$ mag for the progenitor.

3.7. *SN 1999ev in NGC 4274*

SN 1999ev was discovered by T. Boles of the U.K. Nova/Supernova Patrol (Hurst 1999) and was classified as a SN II by Garnavich et al. (1999b). We measure from a KAIT image the SN position as $\alpha = 12^h19^m48\overset{s}{.}20$, $\delta = +29°37'21\overset{''}{.}7$, with uncertainty $\pm0\overset{''}{.}4$. This agrees, to within the errors, with the position measured by Armstrong (1999), but disagrees with the positions measured by Boles and by Garnavich et al. The host galaxy was imaged by GO-5741 in F555W (280 s) on 1995 February 5. We applied the 2MASS grid directly to the WFPC2 mosaic for the four faint stars in common, with uncertainty $\pm0\overset{''}{.}7$, leading to a total uncertainty $\pm0\overset{''}{.}8$. Figure 10 shows the SN site on the WF2 chip. The two brightest of the faint objects within the error circle, labelled A and B, have $m_{\rm F555W} = 24.93\pm0.23$ and 25.28 ± 0.32 mag, respectively. Assuming a distance of about 17 Mpc and Galactic $A_V = 0.07$ mag, these correspond to $M_V^0 \approx -6.3$ and -5.9 mag, respectively. Either of these is consistent with the absolute magnitudes of red supergiants and could be the progenitor. If neither of these two stars is the progenitor, then it had $M_V^0 \gtrsim -5.5$ mag.

3.8. *SN 2000C in NGC 2415*

SN 2000C was independently discovered by S. Foulkes and M. Migliardi (Foulkes et al. 2000). It was classified as a SN Ic by Cappellaro et al. (2000) and Jha et al. (2000). We measure the SN position from a galaxy background-subtracted KAIT image as $\alpha = 07^h36^m57\overset{s}{.}11$s, $\delta = +35°14'39\overset{''}{.}0$, with uncertainty $\pm0\overset{''}{.}2$. This position agrees, to within the errors, more with that measured by Migliardi than with that measured originally by Li.

We (GO-8602) obtained a F555W 700-s Snapshot image (in a cosmic-ray split pair) on 2001 March 11. The host galaxy was also imaged by GO-6862 on 1997 May 19 in F547M (700 s), F656N (600 s), and F814W (560 s), and by GO-9124 on 2002 May 3 in F300W (600 s). We applied the 2MASS astrometric grid directly to the unsaturated and partially saturated stars on the F555W mosaic, with a total uncertainty of $\pm0\overset{''}{.}5$ in the SN position on the mosaic. Figure 11 shows this position on the PC chip. Within the error circle is a point source with relatively high signal-to-noise ratio (S/N), which is almost certainly the SN at late times, with $m_{\rm F555W} = 22.74\pm0.07$ mag. We can be confident of the SN identification, since this object is seen on both of the cosmic-ray splits *and* is not seen in the pre-SN F547M image of similar depth (Figure 12) or in the F814W PC images. The SN is not detected on the F300W WF3 chip on 2002 May 3 to $m_{\rm F300W} \gtrsim 22.9$ mag (however, the star cluster to the west of the SN is quite bright in this band). In neither the F547M nor F814W image is a progenitor candidate detected, to $V \gtrsim 25.1$ and $V-I \lesssim 1.3$ mag. For a distance of about 60 Mpc and Galactic $A_V = 0.14$ mag, this corresponds to $M_V^0 \gtrsim -8.9$ and $(V-I)^0 \lesssim 1.2$ mag for a progenitor.

SN 1998Y, which was discovered by Li et al. (1998) using KAIT and classified as a SN II by Filippenko, Leonard, & Riess (1998), also occurred in this host galaxy. Because of poor seeing, the faintness of the SN, and high galactic background in the KAIT images, it is difficult to obtain a good centroid for the SN in order to accurately determine its position. From a relatively crude position and its proximity to SN 2000C (within 2″), we know that the SN site is also on the Snapshot image (PC chip). We have very carefully subtracted the light of the pre-SN F547M image from that of the Snapshot image and inspected a circular region with radius 60 pixels centered on the SN 2000C position (60 pixels on the PC chip is ∼3″), but we could not locate SN 1998Y. It must have faded below detectability by 2001 March. (It should be noted that the subtraction very nicely reveals SN 2000C.) The limit on the brightness of SN 1998Y in 2001 March is $V \gtrsim 25.9$ mag. We did not try to locate the SN 1998Y progenitor in any of the pre-SN images, owing to the crude position.

3.9. *SN 2000ds in NGC 2768*

SN 2000ds was discovered by Puckett & Dowdle (2000) and classified as a relatively old SN Ib by Filippenko & Chornock (2000). From a KAIT image we measure the SN position as $\alpha = 09^h11^m36\overset{s}{.}28$, $\delta = +60°01'43\overset{''}{.}3$, with uncertainty $\pm0\overset{''}{.}3$. The host galaxy was imaged by GO-6587 on 1999 May 20 in F555W (1000 s and also 400 s) and in F814W (2000 s). Only two of the stars seen on the 1000-s F555W mosaic have 2MASS counterparts; the rest are too faint. For this reason we established a secondary astrometric grid using a deep Palomar V-band image of the host, with uncertainty $\pm0\overset{''}{.}4$. The resulting grid applied to the WFPC2 mosaic has uncertainty $\pm0\overset{''}{.}5$, for a total uncertainty of $\pm0\overset{''}{.}7$ in the SN position on the mosaic. Figure 13 shows the SN site on the WF2 chip. Although hints of faint, reddish clusters of stars may be evident near the SN position at the 3–4σ level ($I \approx 25.7$–24.7 mag), generally no star is detected to $V \gtrsim 26.6$ and $V-I \lesssim 1.6$ mag. For a distance of about 25 Mpc and Galactic $A_V = 0.15$ mag, this corresponds to $M_V^0 \gtrsim -5.5$ and $(V-I)^0 \lesssim 1.5$ mag for the progenitor.

3.10. *SN 2000ew in NGC 3810*

SN 2000ew was discovered by Puckett & Langoussis (2000) and classified as a SN Ic by Filippenko, Chornock, & Modjaz (2000). From a KAIT image we measure the SN position as $\alpha = 11^h40^m58\overset{s}{.}60$, $\delta = +11°27'55\overset{''}{.}8$, with uncertainty $\pm0\overset{''}{.}3$. [This position differs by ∼1″ or more from those reported by Puckett & Langoussis and by Garradd (2000).] The host galaxy was imaged by GO-9042 in F450W and F814 W (460 s each) on 2001 November 7–8 and by GO-5446 in F606W (160 s) on 1994 November 4. The host is quite large on the mosaics, and the Galactic stars on the F814W mosaic are too faint for 2MASS, so we established an astrometric grid using a deep Palomar V-band image. Applying this grid to the WFPC2 mosaic, the uncertainty is $\pm0\overset{''}{.}6$, leading to a total uncertainty of $\pm0\overset{''}{.}7$ in the SN position on the mosaics.

In Figure 14 we show the SN position on the F814W WF3 chip. Toward the southeast edge of the error circle is a point source, which we identify as the fading SN. Our confidence stems primarily from the fact that the point source is seen in both the F450W and F814W (2001 November 7–8) images, *and* it is not seen in the

F606W (1994 November 4) WF4 image (Figure 15). Note how close the position is to the chip edge (<50 pixels). Since HSTPhot masks the first 50 pixels from the chip edge, in this exceptional case we had to use PSF fitting in DAOPHOT/ALLSTAR (Stetson 1987, 1992) within IRAF, with a Tiny Tim PSF (Krist 1995) for both the F450W and F814W bands, and subsequently tie the results to the HSTPhot output for point sources across the rest of the unmasked chip. Finally, we transformed the resulting magnitudes to standard B and I via synthetic photometry generated with the STSDAS package SYNPHOT and the Bruzual Spectral Atlas (see Filippenko et al. 1995; Van Dyk et al. 2002a). We estimate that the SN had $B = 22.78 \pm 0.05$ and $I = 20.97 \pm 0.04$ mag on 2001 November 8.

A progenitor is not detected on the pre-SN image, to $m_{\rm F606W} \gtrsim 24.7$ mag. The Galactic $A_V = 0.15$ mag, but we can use the F450W and F814W image color information to investigate the extinction local to the SN. Figure 16 illustrates the color-magnitude diagram for the SN environment, showing the SN and the three stars immediately next to the SN in Figure 14. The diagram implies that all three stars are quite luminous, intermediate in color, and young. The three stars could all be in the helium-burning phase, following the blue loop expected for massive star evolution, or they could all be very blue supergiant stars experiencing $A_V \approx 1$–1.5 mag. The fact that the environment appears to contain blue or yellow, young ($\lesssim$ 6 Myr), and therefore massive, stars suggests that the SN progenitor could have been quite massive as well. For a distance of about 16 Mpc and assuming simply the Galactic value of A_V, a progenitor had $M_V^0 \gtrsim -6.5$ mag. For the possibly larger extinction range, this corresponds to $M_V^0 \gtrsim -7.3$ to -7.8 mag. We clearly require more color information to better understand the SN's environment and its possible progenitor.

3.11. *SN 2001B in IC 391*

SN 2001B was discovered by the BAO SN search (Xu & Qiu 2001) and classified as a probable SN Ib by Chornock & Filippenko [2001; note that Matheson et al. (2001b) had earlier classified it as SN Ia]. From a Mt. Hopkins V-band image (kindly provided by T. Matheson) we measure the SN position as $\alpha = 04^h57^m19^s.31$, $\delta = +78°11'16''.6$, with uncertainty $\pm0''.2$. The host galaxy was imaged by GO-5104 in a single 70-s F555W exposure on 1994 February 21. We use four stars from the Mt. Hopkins image to establish the astrometric grid on the WFPC2 mosaic, with total uncertainty $\pm0''.3$. Figure 17 shows the SN site on the WF3 chip. Within the error circle is a point source with $m_{\rm F555W} = 23.38 \pm 0.18$ mag. For a distance of about 28 Mpc and Galactic $A_V = 0.42$ mag, we find $M_V^0 \approx -9.3$ mag for this star, which we tentatively identify as the SN progenitor. Unfortunately, we do not have any color information for the candidate. However, if this star is not the progenitor, then for a detection limit $m_{\rm F555W} \gtrsim 24.3$ mag, the progenitor had $M_V^0 \gtrsim -8.4$ mag.

3.12. *SN 2001ai in NGC 5278*

SN 2001ai was discovered by LOTOSS (Modjaz, Li, & Schwartz 2001a) and classified as a SN Ic by Matheson et al. (2001c). From a KAIT image we measure the SN position as $\alpha = 13^h41^m39^s.37$, $\delta = +55°40'05''.8$, with uncertainty $\pm0''.3$. The host galaxy was imaged in F255W, F300W, and F814W (total exposure times 1400 s, 1500 s, and 260 s, respectively) on 2000 December 18 by GO-8645. Since the stars seen in the F814W mosaic are too faint for 2MASS counterparts, we establish the astrometric grid from a Palomar V-band image, with uncertainty $\pm0''.3$. We show in Figures 18 and 19 the SN site on the WF3 chip, with total uncertainty $\pm0''.4$, in F814W and F300W, respectively.

Two objects which HSTphot considers extended, A and B, are detected in both F300W and F814W at the periphery of the error circle, with $m_{\rm F300W} = 21.10 \pm 0.01$, $m_{\rm F814W} = 21.35 \pm 0.01$ mag, and $m_{\rm F300W} = 20.96 \pm 0.01$, $m_{\rm F814W} = 22.14 \pm 0.01$ mag, respectively. Additionally, Object C, considered stellar by HSTphot, is detected at F300W only at the southern edge of the circle, with $m_{\rm F300W} = 22.57 \pm 0.32$ mag. (The F255W image is not of sufficiently high S/N to provide additional information on the environment; the detection limit is $m_{\rm F255W} \gtrsim 20.5$ mag.) No other objects are detected within the error circle to $m_{\rm F300W} \gtrsim 23.2$ and $m_{\rm F814W} \gtrsim 23.9$ mag.

The SN host is quite distant (~120 Mpc), and for Galactic $A_V = 0.03$ mag, Objects A and B have $M_I^0 \approx -14.0$, $(U-I)^0 \approx -0.3$ mag, and $M_I^0 \approx -13.3$, $(U-I)^0 \approx -1.2$ mag, respectively. Object C has $M_U \approx -12.8$, $(U-I)^0 \lesssim -1.3$ mag (based on the $m_{\rm F814W}$ detection limit), which is likely too bright for a single star. At 120 Mpc, in this case what HSTphot considers stellar is probably still an extended object (e.g., a compact cluster). The progenitor could have been associated with one of these three objects, which are probably star clusters, and was not resolved. Alternatively, the progenitor was not associated with these objects and also not detected, to $M_I^0 \gtrsim -11.5$ mag, the upper end of which greatly exceeds even the most luminous supergiants. The relatively unrestrictive color limit for an undetected progenitor is $(U-I)^0 \lesssim -0.3$ mag.

3.13. *SN 2001ci in NGC 3079*

SN 2001ci was discovered on 2001 April 25 by LOTOSS using KAIT (Swift, Li, & Filippenko 2001). Swift et al. remarked on the low apparent luminosity of the SN. Filippenko & Chornock (2001) identified it as a SN Ic, but possibly extinguished by $A_V \approx 5$–6 mag. We measure from a KAIT image a position of $\alpha = 10^h01^m57^s.21$, $\delta = +55°41'14''.0$, with uncertainty $\pm0''.3$. The host galaxy was imaged on 2001 January 21 in F606W (560 s) by GO-8597, and on 1999 March 4 by GO-7278 in F547M (320 s) and F814W (140 s), all pre-SN observations. The stars on the F606W mosaic were too faint for 2MASS, so we used a deep Palomar V-band image to establish the astrometric grid, with uncertainty $\pm0''.2$, and total uncertainty $\pm0''.3$. The host was also imaged on 2001 December 9, well after discovery, in F300W (~U; 800 s) by GO-9124, but the SN is not detected to $m_{\rm F300W} \gtrsim 23.5$ mag. We show in Figure 20 the SN site on the F814W WF3 chip. A hint of an object can be seen within the error circle, but no star is detected by HSTphot to $V \gtrsim 24.7$, $V-I \lesssim 1.8$ mag, based on the F547M and F814W images. The F606W limit is significantly deeper, at $V \gtrsim 26.4$ mag. Assuming the above range in extinction and a distance of about 21 Mpc, the F606W limit corresponds to $M_V^0 \gtrsim -10.2$ to -11.2 mag.

The color limit is $(V-I)^0 \lesssim -0.2$ to -0.6 mag.

3.14. *SN 2001du in NGC 1365*

SN 2001du was visually discovered by Evans (2001), about 90″ W and 10″ S of the nucleus of the nearby barred spiral galaxy NGC 1365. The SN was classified as Type II-P by Wang et al. (2001). We have independently measured the position from three different SN images available on the Internet: an image by G. Bock, a deeper image by T. Dobosz, and an image obtained with the YALO 1-m at CTIO. We derive three slightly different positions, respectively: $\alpha = 3^h33^m29\overset{s}{.}15$, $\delta = -36°08'32\overset{''}{.}0$; $\alpha = 3^h33^m29\overset{s}{.}14$, $\delta = -36°08'32\overset{''}{.}0$; and, $\alpha = 3^h33^m29\overset{s}{.}15$, $\delta = -36°08'31\overset{''}{.}5$. (Uncertainties in each are $\sim0\overset{''}{.}7$, $\sim0\overset{''}{.}5$, and $\sim0\overset{''}{.}3$, respectively.) Together, these measurements differ from each other by $\sim0\overset{''}{.}7$. The measurements all differ by $\gtrsim0\overset{''}{.}5$ from that measured by Jacques (2001). We adopt the position measured from the YALO image, with the smallest error. This adopted position is $\sim0\overset{''}{.}7$ from the position we initially quoted in Van Dyk et al. (2001); the difference is likely due to the improved astrometric solution, but is consistent with the overall uncertainties discussed here. Given the uncertainty in the measured positions, and the relative disagreement with previously measured positions, we adopt a total positional uncertainty of $\pm0\overset{''}{.}8$.

The SN site is in 100-s F336W, F555W, and F814W exposures obtained by GTO-5222 on 1995 January 15. [Unfortunately, the Cepheid Key Project (Silbermann et al. 1999) very deep images are of the opposite arm of NGC 1365.] We could apply the 2MASS astrometric grid using only three relatively bright stars on the F555W mosaic. We estimate the uncertainty in this application, based on one other object on the mosaic, and find $\pm0\overset{''}{.}4$, which leads to a grand total uncertainty of $\pm0\overset{''}{.}9$. Figure 21 shows the SN site on the F555W WF3 chip. Three objects, A–C, are detected within the error circle (a source that looks somewhat extended is toward the center of the circle, but it is undetected by HSTphot). Object A, to the south, is blue, with $m_{\rm F555W} = 24.30\pm0.21$ mag and no detection at F814W; Object B, to the west, is also blue, with $m_{\rm F555W} = 25.02\pm0.32$ mag and no F814W counterpart; and Object C, to the east, is relatively red, with $V = 24.44\pm0.23$ and $V-I = 1.03\pm0.30$ mag. (The F336W exposures are of insufficient S/N to show any object at the SN site.) Since SN 2001du is of Type II-P, we assume that of the three detected candidates, this red eastern star is the most plausible progenitor (but still unlikely; see below).

The Galactic extinction toward the host is $A_V = 0.07$ mag, but we possibly can use the color information from the F555W and F814W images to estimate the extinction local to the SN, as well as study the properties of the SN's stellar environment. Figure 22 shows the $(V-I, V)$ color-magnitude diagram for the environment. The reddish progenitor candidate, Star C, is indicated. It is interesting that no red (M-type) supergiant stars, the presumed SN II progenitors, with $V-I \gtrsim 1.8$ and $V \gtrsim 25$ mag, are detected in the environment, likely due to the low S/N of these images. It is also notable that many of the detected stars, including Star C, have $V \approx 24.7$ and $V-I \approx 1.1$ mag. These presumably K-type supergiants either all have ages ∼12–16 Myr and are in the blue loop core He-burning phase, or they are intrinsically far bluer and younger supergiants experiencing similar, larger amounts of extinction, $A_V \approx 2.5$ mag.

Given the distance modulus $\mu = 31.3$ mag to NGC 1365 determined from *HST* observations of Cepheids (Silbermann et al. 1999) and only the Galactic extinction, if Star C is the progenitor it has $M_V^0 \approx -6.9$ and $(V-I)^0 \approx 1.0$ mag. With possibly higher local extinction, $A_V \approx 2.5$ mag, this becomes $M_V^0 \approx -9.4$ and $(V-I)^0 \approx 0.0$ mag. We consider it more likely that the relevant archival data were just not sensitive enough to detect the true progenitor of SN 2001du. Assuming only Galactic extinction, the progenitor had $M_V^0 \gtrsim -6.3$ and $(V-I)^0 \lesssim 1.5$ mag. Program GO-9041 has imaged SN 2001du in several bands with WFPC2, and these data will be public in late November 2002. At that time, or possibly earlier, we will know the exact location of the SN and potentially learn more about the nature of the progenitor.

3.15. *SN 2001is in NGC 1961*

SN 2001is was independently discovered by both the BAO and LOTOSS searches (Qiu et al. 2001). Benetti et al. (2001) identified it as a SN Ib, with possible residual H contamination. From a KAIT image we measure the SN position as $\alpha = 05^h42^m09\overset{s}{.}12$, $\delta = +69°21'54\overset{''}{.}5$, with uncertainty $\pm0\overset{''}{.}4$. The host galaxy was imaged (GO-5419) on 1994 August 28 in a cosmic-ray split F218W exposure (1800 s total) and in a single 300-s F547M exposure. The host was also imaged deeply by GO-9106 in the FR680N and F547M bands (4000 s each) on 2001 July 14. (The low S/N of the FR680N images near the SN site does not make them particularly useful.) The KAIT image was sufficiently deep that we could identify some of the stars in each of the F547M mosaics, with astrometric uncertainty $\pm0\overset{''}{.}2$, for a total uncertainty of $\pm0\overset{''}{.}4$ in the SN's position on the mosaics. In Figure 23 we show the SN site on the deep F547M WF3 chip. Two stars, A and B, are detected within at $m_{\rm F547M} = 26.11\pm0.27$ and 25.77 ± 0.20 mag. Assuming a distance of about 64 Mpc and Galactic $A_V = 0.41$ mag, we find $M_V^0 \approx -8.3$ and -8.7 mag for the two stars, respectively, either of which could be the progenitor. If neither of these stars is the progenitor, then for a detection limit of $m_{\rm F547M} \gtrsim 26.4$ mag, the progenitor had $M_V^0 \gtrsim -8.0$ mag.

4. DISCUSSION

In Table 2 we summarize the results of our search for the progenitors of core-collapse SNe. For SNe with candidate progenitor identifications, we have also included, in parentheses, the limits on the absolute magnitude and color of a possible progenitor, if the candidate we have identified is not the actual progenitor. It should be noted that for all the magnitude and color estimates, we have assumed possibly inaccurate distance estimates and, in most cases, only the Galactic component to the extinction toward the SN. Consequently, we may have either underestimated or overestimated the absolute magnitude, or limits on the absolute magnitude, of candidate progenitors. Extinction local to the SNe within the host galaxies themselves will only lead to higher absolute brightnesses, and to bluer intrinsic colors, or color limits, for all these objects. At the least, we provide the measured magnitudes and magnitude limits for the SN progenitors, based on the HSTphot output, so that, with additional information, the reader can make his or her own estimations. Below, we briefly interpret our results, but we eschew transforming the observed magnitudes and colors into intrinsic properties, such as bolometric luminosity and surface temperature, for lack of adequate information about the stars.

The candidate SNe II progenitors of SNe 1999br, 1999ev, and 2001du all have absolute magnitudes ($M_V^0 \approx -5.9$ to -6.9) that are consistent with the known red supergiants in the Galaxy. All of the magnitude limits for the other SNe II are also consistent with supergiant stars. The only candidate with intrinsic color information, the progenitor candidate for SN 2001du, has a $(V-I)^0$ value more consistent with an early K spectral type (e.g., the Vilnius spectral colors in Bessell 1990), rather than the M-type supergiant that we would expect, based on theoretical models. In fact, even if this candidate is not the progenitor, the $(V-I)^0$ color limit for the SN 2001du progenitor, as well as the color limits for the SN 1999bx progenitor [if we discount the $(U-V)^0$ limit], imply spectral types that can only be as late as early M-type. The slightly bluer color might imply a somewhat more compact morphology for the progenitor envelope, or possible contamination of its light by a close, fainter and bluer companion star in a possible binary system.

Models for SNe Ib include the explosion of isolated Wolf-Rayet stars or of helium stars in binary systems, possibly with a wide orbit including a more massive main-sequence secondary (e.g., van den Heuvel 1994). Both mechanisms could lead to SNe Ib. However, Branch et al. (2002) find, from their analysis of SN Ib spectral data, that the masses and kinetic energies among SNe Ib are similar, implying that progenitor masses must be similar as well. Wolf-Rayet stars that have been stripped of much of their helium could lead to SNe Ic; however, model light curves decline too slowly, compared to observations (Woosley, Langer, & Weaver 1993). Low-mass helium stars in binaries (e.g., Nomoto et al. 1990) end up with too much helium for SNe Ic. Nomoto et al. (1994) explored a $\sim$2–3 $M_\odot$ C+O star (which originally evolved from a 13–18 $M_\odot$ main-sequence star) in a close binary as the progenitor of the SN Ic 1994I in M51. Their model, possibly including a common-envelope phase, involves two episodes of mass transfer with a secondary, which eventually evolves to be a low-mass main sequence star, a neutron star, or a white dwarf. All of these scenarios involve compact stars, which are likely not particularly luminous; Barth et al. (1996) place an upper limit of $M_V \gtrsim -7.3$ mag on the SN 1994I progenitor. As Podsiadlowski et al. (1992) point out, mass transfer, in fact, could make the secondary more massive and more luminous when the primary explodes, meaning that a detected "progenitor" could actually be the companion star.

The candidate progenitor for the SN Ic 1999bu is quite luminous, with $M_V^0 \approx -7.5$ mag, which is consistent with the upper limit for the SN 1994I progenitor mentioned above. The candidate progenitors for the SNe Ib 2001B and 2001is are also very luminous, with $M_V^0 \approx -8$ to -9 mag. The known Wolf-Rayet stars in the Galaxy have absolute magnitudes spread over a large range, $M_V^0 \approx -2$ to -8 mag (van der Hucht 2001). The SN Ib progenitor candidate luminosities are near or slightly above the upper end of this luminosity range. Therefore, it is possible that these two SNe Ib arose from Wolf-Rayet stars. (However, with the uncertainties in the distances to and reddening within the host galaxies, these absolute magnitudes may actually fall outside the Wolf-Rayet luminosity range, i.e., they would be too bright.) The luminosities for these SN Ib progenitor candidates are also consistent with those of other, less evolved, presumably blue or yellow supergiants (Humphreys & Davidson 1979). Alternatively, it is possible that these candidates are not the progenitors, but instead multiple star systems or compact star clusters.

Generally, the absolute magnitude limits for all other SNe Ib/c (the brightness limits for SNe 2001ai and 2001ci are not very restrictive) are consistent both with the range of Wolf-Rayet magnitudes and also with expectations for interacting binary models. The intrinsic color limits, although also usually not very restrictive, are consistent with blue or yellow stars. The most restrictive color limits are for the progenitors of SNe 1999ec and 2001ci (if, in this case, the extinction estimate $A_V \approx$ 5–6 mag is, in fact, correct): taken together, these limits imply that the progenitors had spectral types of A-type or earlier (Bessell 1990) and are also consistent with the range of $B-V$ (about -0.5 to -0.1 mag) for Galactic Wolf-Rayet stars (van der Hucht 2001). The host galaxy of SN 2001ci, NGC 3079, is seen nearly edge-on, so it is possible that the SN progenitor could have been a Wolf-Rayet star exploding while obscured by or embedded in dust.

To some extent, our search was not fully satisfying. Although it is true that, compared with the case of Van Dyk et al. (1999b), the *HST* archive is currently much richer in pre-SN host galaxy images, which may potentially contain SN progenitors, and more importantly, post-SN images in which the fading SNe may be recovered, the quality of these data is such that the S/N or number of filters used are generally still not ideal. The data in our sample are not yet sensitive enough for us to place more stringent constraints on the competing models for SNe Ib/c. The *HST* archive will steadily grow, however, as observations continue after the recent refurbishment mission. These new observations will also include images of galaxies with the superior Advanced Camera for Surveys (ACS). Additionally, new nearby SNe will be discovered by LOSS/LOTOSS and other SN searches, greatly expanding the potential sample. We intend to further exploit the *HST* archive to continue to search for core-collapse SN progenitors; the future looks bright for this subject.

5. CONCLUSIONS

We have searched for the progenitor stars of 16 core-collapse SNe using archival *HST* WFPC2 images. The sample includes 6 SNe II and 10 SNe Ib/c. We may have identified the progenitors of the SNe II 1999br, 1999ev, and 2001du as supergiant stars with $M_V^0 \approx -6$ mag in all three cases. We may also have identified the progenitors of the SNe Ib 2001B and 2001is as very luminous supergiants with $M_V^0 \approx -8$ to -9 mag, and possibly the progenitor of the SN Ic 1999bu as a supergiant with $M_V^0 \approx -7.5$ mag. If these identifications can be verified, this more than doubles the number of known SN progenitors from five to eleven. For all other SNe in our sample we could only place limits on the progenitor absolute magnitude and color (when multi-band images were available). We have also recovered SNe 1999dn, 2000C, and 2000ew at late times. Unfortunately, the pre-SN images for these recovered SNe did not show a progenitor candidate at the SN position.

The possible detections and constraints on the SN II progenitors are broadly consistent with red supergiants as progenitor stars, although the progenitor candidates are not as red as would be expected, with their colors implying spectral types typically earlier than M. The SN Ib progenitor candidates may well be Wolf-Rayet stars, although possibly at the upper luminosity end for known stars of this kind. The lone SN Ic progenitor candidate is consistent with a luminous supergiant star. In general, we cannot place rigorous constraints on either the Wolf-Rayet star or massive interacting binary models for SN Ib/c progenitors, based on these data. For both the SNe II and Ib/c uncertainties in the host galaxy distances and extinction toward the SNe also limit what conclusions we can draw about the progenitor stars. However, from purely environmental considerations, our results are consistent with those of Van Dyk et al. (1999b), who found that SNe Ib/c seem to be more closely associated with massive stellar regions than is true for SNe II; five of the SNe Ib/c in our sample (SNe 1999ec, 2000C, 2000ew, 2001ai, and 2001is) occurred very near bright, possibly blue and young star clusters (the cluster near SN 2000C, based on the F300W image, is quite blue, and the cluster near SN 2000ew, based on the color-magnitude diagram, is quite young). Again, the statistics are still small, but this continues to suggest that at least some SN Ib/c progenitors may be more massive, in general, than SN II progenitors, consistent with the Wolf-Rayet model.

A current program (GO-9353) is imaging six of the SNe in our sample (1999an, 1999br, 1999ev, 2000ds, 2000ew, and 2001B) in multiple bands with ACS, to attempt to recover them at late times, with the same aim of matching the pre-SN and post-SN images to identify the SN progenitor. Similarly, program GO-9041 has imaged SN 2001du with WFPC2, but the data are not yet public. For SNe 1999an, 2000ds, and 2000ew, we have already likely recovered SN 2000ew, and we have already shown here that the pre-SN images are simply not of sufficient S/N to detect each SN progenitor. For SNe 1999br, 1999ev, 2001B, and 2001du, the new observations from these programs will be quite revealing: if the SNe are actually recovered, they may or may not match up positionally with the progenitor candidates that we have identified.

In this paper we have made some progress toward a statistically significant sample of core-collapse SN progenitors directly identified on *HST* image data. However, the limitations of the data continue to be the restricted field of view, low S/N, and poor color coverage. With the full operation of the newly commissioned ACS onboard *HST*, and with additional galaxies observed using WFPC2 as well, the amount of available archive data will continue to grow, providing for larger SN samples in the future.

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Table 1
Summary of Available Data

SN	Host Galaxy	Date (UT)	Filters	Exp. Time (s)	*HST* Program
1998Y	NGC 2415	1997 May 19	F547M	700	GO-6862
			F656N	600	
			F814W	560	
		2001 Mar 11	F555W	700	GO-8602[a]
		2002 May 03	F300W	600	GO-9124
1999an	IC 755	1995 Jan 05	F606W	160	GO-5446
1999br	NGC 4900	1995 Jan 29	F606W	160	GO-5446
		2002 Jun 20	F450W	460	GO-9042
			F814W	460	
1999bu	NGC 3786	1995 Mar 30	F606W	500	GO-5479
1999bx	NGC 6745	1997 Mar 19,21	F336W	22000	GO-6276
			F555W	4800	
			F675W	5200	
			F814W	5200	
1999dn	NGC 7714	1996 May 15	F606W	500	GO-5479
		1998 Aug 29	F380W	1800	GO-6672
		2001 Jan 24	F814W	700	GO-8602[a]
		2001 Jul 10	F555W	700	
			F814W	700	
		2001 Aug 03	F300W	300	GO-9124
1999ec	NGC 2207	1996 May 25	F336W	2000	GO-6483
			F439W	2000	
			F555W	660	
			F439W	720	
1999ev	NGC 4274	1995 Feb 05	F555W	280	GO-5741
2000C	NGC 2415	1997 May 19	F547M	700	GO-6862
			F656N	600	
			F814W	560	
		2001 Mar 11	F555W	700	GO-8602[a]
		2002 May 03	F300W	600	GO-9124
2000ds	NGC 2768	1999 May 20	F555W	400	GO-6587
				1000	
			F814W	2000	
2000ew	NGC 3810	1994 Nov 04	F606W	160	GO-5446
		2001 Nov 07,08	F450W	460	GO-9042
			F814W	460	
2001B	IC 391	1994 Feb 21	F555W	70	GO-5104
2001ai	NGC 5278	2000 Dec 18	F255W	1400	GO-8645
			F300W	1500	
			F814W	260	
2001ci	NGC 3079	1999 Mar 04	F547M	320	GO-7278
			F814W	140	
		2001 Jan 21	F606W	560	GO-8597

TABLE 1—*Continued*

SN	Host Galaxy	Date (UT)	Filters	Exp. Time (s)	*HST* Program
		2001 Dec 09	F300W	800	GO-9124
2001du	NGC 1365	1995 Jan 15	F336W	100	GTO-5222
			F555W	100	
			F814W	100	
2001is	NGC 1961	1994 Aug 28	F218W	1800	GO-5419
			F547M	300	
		2001 Jul 14	F547M	4000	GO-9106
			FR680N	4000	

[a]This is part of our own Snapshot program (PI: Filippenko); see Li et al. (2002).

Table 2
Summary of Progenitor Properties

SN	Absolute Magnitude[a]	Color[a] (mag)
	SNe II	
1998Y[b]	...	...
1999an	$M_V^0 \gtrsim -6.9$	...
1999br	$M_V^0 \approx -6.3$	...
	$(M_V^0 \gtrsim -5.9)$[c]	...
1999bx	$M_V^0 \gtrsim -7.8$	$(U-V)^0 \lesssim 0.5$
		$(V-R)^0 \lesssim 0.9$
		$(R-I)^0 \lesssim 1.0$
		$(V-I)^0 \lesssim 1.6$
1999ev	$M_V^0 \approx -5.9$ to -6.3	...
	$(M_V^0 \gtrsim -5.5)$	...
2001du	$M_V^0 \approx -6.9$	$(V-I)^0 \approx 1.0$
	$(M_V^0 \gtrsim -6.3)$	$([V-I]^0 \lesssim 1.5)$
	SNe Ib/c	
1999bu	$M_V^0 \approx -7.5$	...
	$(M_V^0 \gtrsim -7.1)$	...
1999dn	$M_V^0 \gtrsim -7.3$	$(U-V)^0 \lesssim 2.5$
1999ec	$M_V^0 \gtrsim -8.7$	$(U-B)^0 \lesssim -0.3$
		$(B-V)^0 \lesssim 0.2$
		$(V-I)^0 \lesssim 0.9$
2000C	$M_V^0 \gtrsim -8.9$	$(V-I)^0 \lesssim 1.2$
2000ds	$M_V^0 \gtrsim -5.5$	$(V-I)^0 \lesssim 1.5$
2000ew	$M_V^0 \gtrsim -6.5$	...
2001B	$M_V^0 \approx -9.3$	...
	$(M_V^0 \gtrsim -8.4)$	...
2001ai	$M_I^0 \gtrsim -11.5$	$(U-I)^0 \lesssim -0.3$
2001ci	$M_V^0 \gtrsim -10.2$ to -11.2	$(V-I)^0 \lesssim -0.2$ to -0.6
2001is	$M_V^0 \approx -8.3$ to -8.7	...
	$(M_V^0 \gtrsim -8.0)$	...

[a]The distance to the host galaxy is generally derived from the heliocentric radial velocity corrected for Local Group infall into the Virgo Cluster given in the LEDA database, with distance scale 65 km s^{-1} Mpc^{-1}. The extinction and reddening to the SN are generally derived from the Galactic component, adopted from NED, and assuming the Cardelli et al. (1989) reddening law. See text for details.

[b]We could not locate SN 1998Y in our own Snapshot (GO-8602) images, nor could we determine a reliable position for the SN in the archival images.

[c]We have also included, in parentheses, the upper limits on the absolute magnitude and color of a possible progenitor here and throughout the table.

Fig. 1.— The site of SN 1999an in IC 755 in an archival 160-s F606W image from 1995 January 5. The error circle has radius 0.″8. Six point-like objects are detected within the circle, but with $M_V^0 \approx -9.0$ to -10.0 mag, they are somewhat too bright to be single stars and are more likely compact star clusters.

Fig. 2.— The site of SN 1999br in NGC 4900 in an archival 160-s F606W image from 1995 January 29. The error circle has radius 0.″5. A possible progenitor star, with $M_V^0 \approx -6.3$ mag, is identified along the north-northeast edge of the circle and indicated with tick marks.

Fig. 3.— The site of SN 1999br in NGC 4900 in an archival 460-s F814W image from 2002 June 20. The error circle has radius 0.″5. The SN is not recovered in this image to $I \gtrsim 24.5$ mag.

Fig. 4.— The site of SN 1999bu in NGC 3786 in an archival 500-s F606W image from 1995 March 30. The site was located by offsetting from a bright star to the northwest of the site, with an estimated error circle of radius 0.″5. Three detected objects, A–C, are indicated with tickmarks. Object C, with $M_V^0 \approx -7.5$ mag, could possibly be the progenitor of this SN Ic.

Fig. 5.— The site of SN 1999bx in NGC 6745 in an archival 4800-s F555W image from 1997 March 21. The error circle has radius 0.″4. Four objects, A–D, along the circle are indicated with tickmarks. They are probably too bright and too blue to be the progenitor star for this SN II.

Fig. 6.— SN 1999dn in NGC 7714, as seen in our 700-s F814W Snapshot image from 2001 January 24. The SN is most likely the star indicated with tickmarks within the 0.″6 error circle. It had $m_{\rm F814W} = 24.18 \pm 0.18$ mag. By July 10 the SN had faded below detectability in both the F555W and F814W bands. We have applied the routine *qzap* to remove residual cosmic-ray hits.

Fig. 7.— The site of SN 1999dn in NGC 7714 in a single archival 500-s F606W exposure from 1996 May 15. We have applied the routine *qzap* to make the image more cosmetically appealing. The error circle has radius 0.″6. No star is detected at the exact position of the SN in Figure 6, indicated with tickmarks.

Fig. 8.— The site of SN 1999ec in NGC 2207 in an archival 660-s F555W image from 1996 May 25. The error circle has radius 0.″3. Two objects identified as stellar by HSTphot are indicated with tickmarks (see Figure 9). Star 1, with $M_V^0 \approx -11.2$ mag, is likely too bright to be a single star. The progenitor, therefore, is likely not detected.

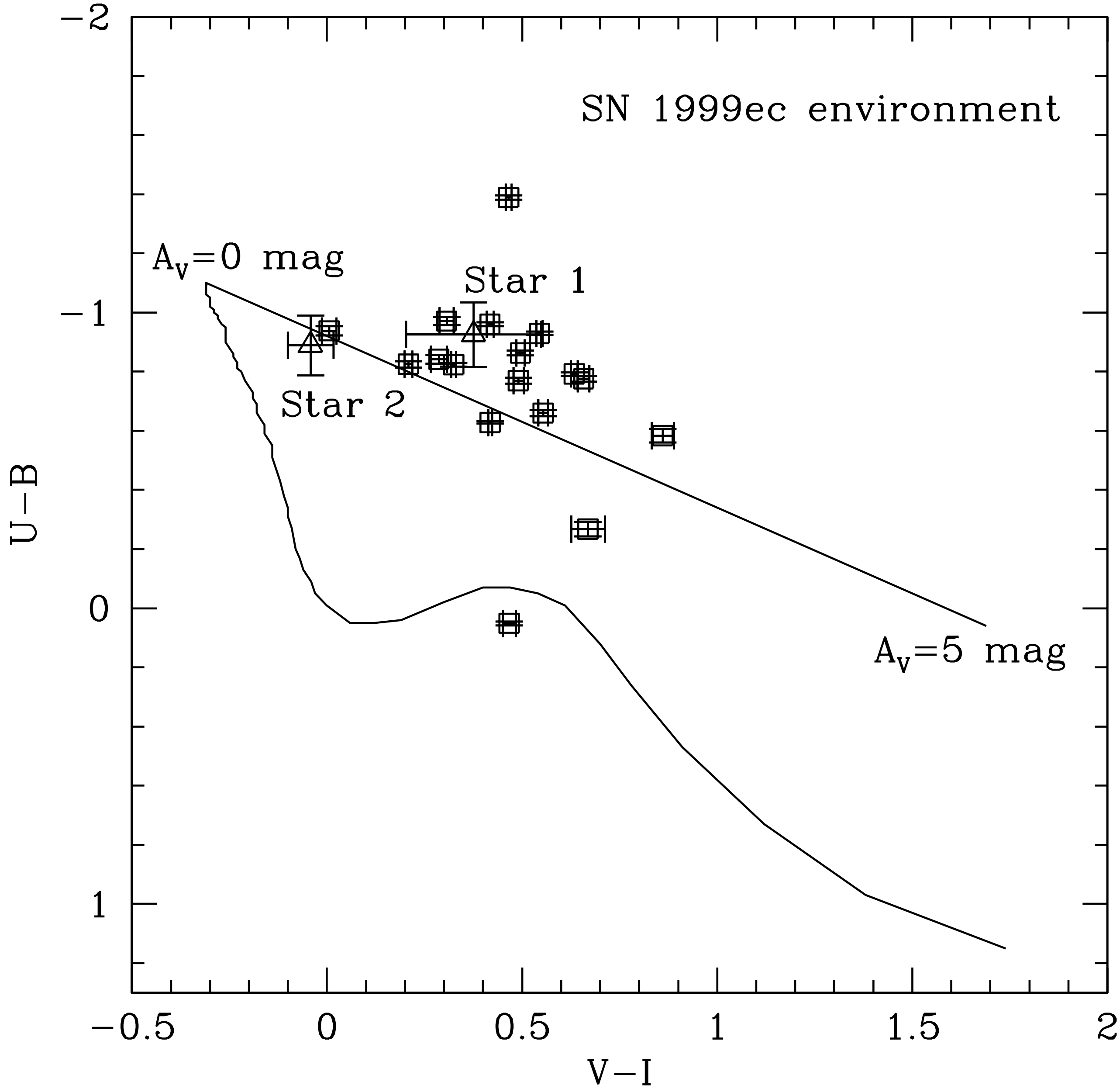

Fig. 9.— The $(U-B,\ V-I)$ color-color diagram for the SN 1999ec environment. The two stellar objects indicated in Figure 8 are represented by *open triangles*; the extended objects are represented by *open squares*. The locus of the main sequence is shown, as is the reddening vector, following the Cardelli et al. (1989) reddening law.

Fig. 10.— The site of SN 1999ev in NGC 4274 in an archival 280-s F555W image from 1995 February 5. The error circle has radius 0.″8. Two faint objects within the error circle, A and B, with $M_V^0 \approx -6.3$ and -5.9 mag, respectively, are indicated with tickmarks. Either of the two could be the progenitor of this SN II.

Fig. 11.— The site of SN 2000C in NGC 2415 in a 700-s F555W Snapshot image from 2001 March 11. The error circle has radius 0.″5. The SN is almost certainly the star with $m_{\rm F555W} = 22.74$ mag, indicated with tickmarks within the circle.

Fig. 12.— The site of SN 2000C in NGC 2415 in an archival 700-s F547M image from 1997 May 19. The error circle has radius 0.″5. No star is detected at the exact position of the SN in Figure 10, indicated with tickmarks.

Fig. 13.— The site of SN 2000ds in NGC 2768 in an archival 1000-s F555W image from 1999 May 20. The error circle has radius 0.″7. The progenitor is not detected.

Fig. 14.— The site of SN 2000ew in NGC 3810 in an archival 460-s F814W image from 2001 November 8. The error circle has radius 0.″7. The SN is almost certainly the star, indicated with tickmarks, toward the southeast edge of the circle. It had $I = 20.97$ and $B - I = 1.81$ mag at that epoch. Note how close the site is to the edge of the WF3 chip.

Fig. 15.— The site of SN 2000ew in NGC 3810 in an archival 160-s F606W image from 1994 November 04. The error circle has radius 0.″7. No star is detected at the exact position of the SN in Figure 13, indicated with tickmarks.

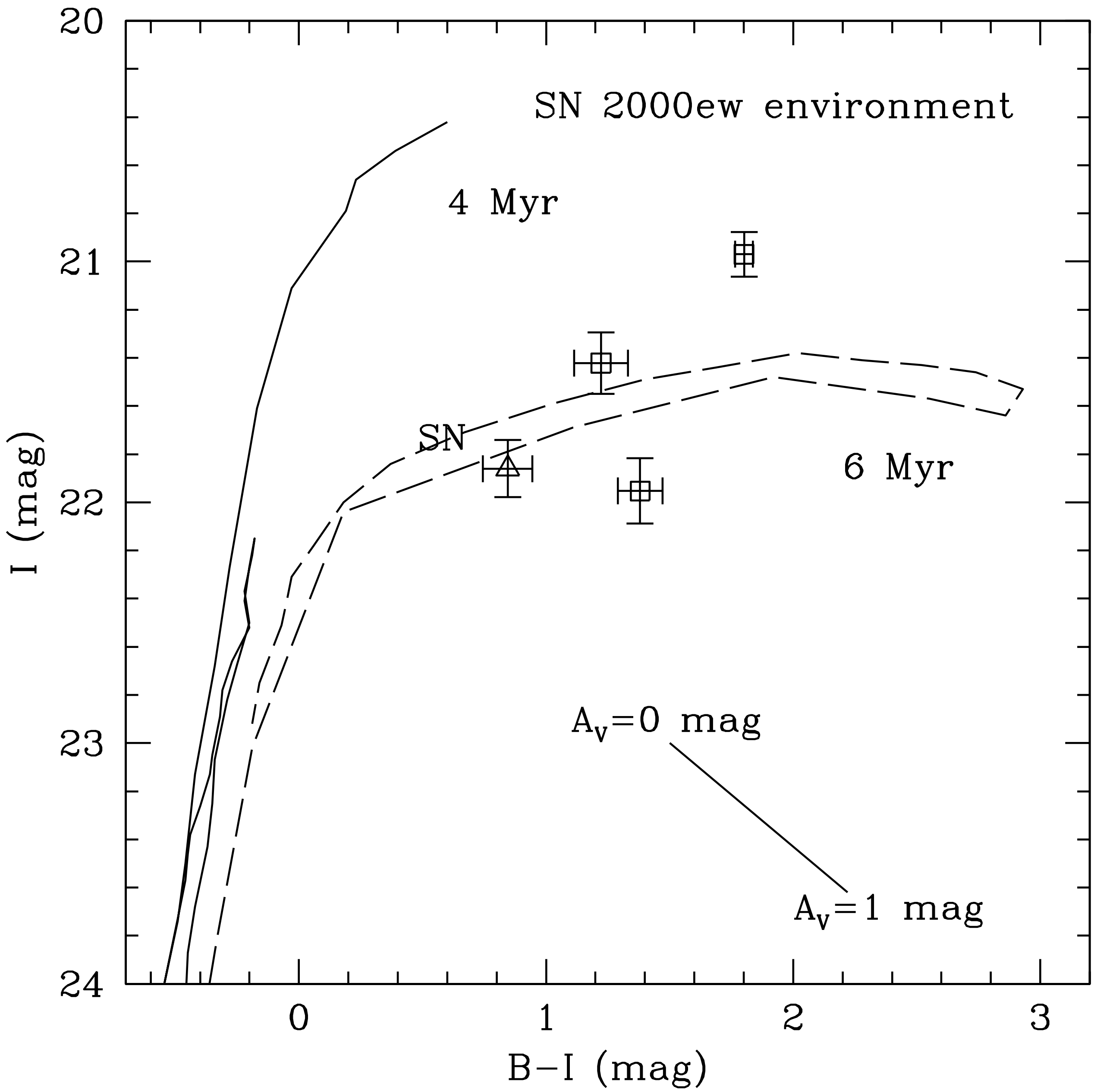

Fig. 16.— The $(B - I,\ I)$ color-magnitude diagram for the SN 2000ew environment. The detected objects are the SN itself (*open triangle*) and the three objects (*open squares*) seen in immediate proximity to the SN in Figure 14. Also shown on the diagram are 4 and 6 Myr isochrones from Bertelli et al. (1994), adjusted for the assumed distance of 15 Mpc and reddened, assuming the Galactic $A_V = 0.15$ mag and the reddening vector, following the Cardelli et al. (1989) reddening law.

Fig. 17.— The site of SN 2001B in IC 391 in an archival 70-s F555W image from 1994 February 21. The error circle has radius $0\farcs3$. A star with $M_V^0 \approx -9.3$ mag, which could be the progenitor, is indicated with tickmarks toward the northern edge of the circle.

Fig. 18.— The site of SN 2001ai in NGC 5278 in an archival 260-s F814W image from 2000 December 18. The error circle has radius $0\farcs4$. Objects A and B along the edge of the circle are indicated with tickmarks.

Fig. 19.— The site of SN 2001ai in NGC 5278 in an archival 1500-s F300W image from 2000 December 18. The error circle has radius $0\farcs4$. Objects A–C along the edge of the circle are indicated with tickmarks. Object C is considered by HSTphot to be stellar and is not detected at F814W.

Fig. 20.— The site of SN 2001ci in NGC 3079 in an archival 140-s F814W image from 1999 March 4. The error circle has radius $0\farcs3$. Although the F606W image from 2001 January 21 is deeper (560 s), the F814W (I) image is less affected by dust extinction in the host galaxy (the SN may be extinguished by $A_V \approx 5$–6 mag) and would better reveal a reddened progenitor. The progenitor is not detected in any of the archive images.

Fig. 21.— The site of SN 2001du in NGC 1365 in an archival 100-s F555W image from 1995 January 15. The error circle has radius $0\farcs9$. Three stars, A–C, within the circle are indicated with tickmarks. Stars A and B are blue, while Star C, with $M_V^0 \approx -6.9$ and $(V-I)^0 \approx 1.0$ mag, is red, and is therefore a possible candidate for the progenitor of this SN II-P.

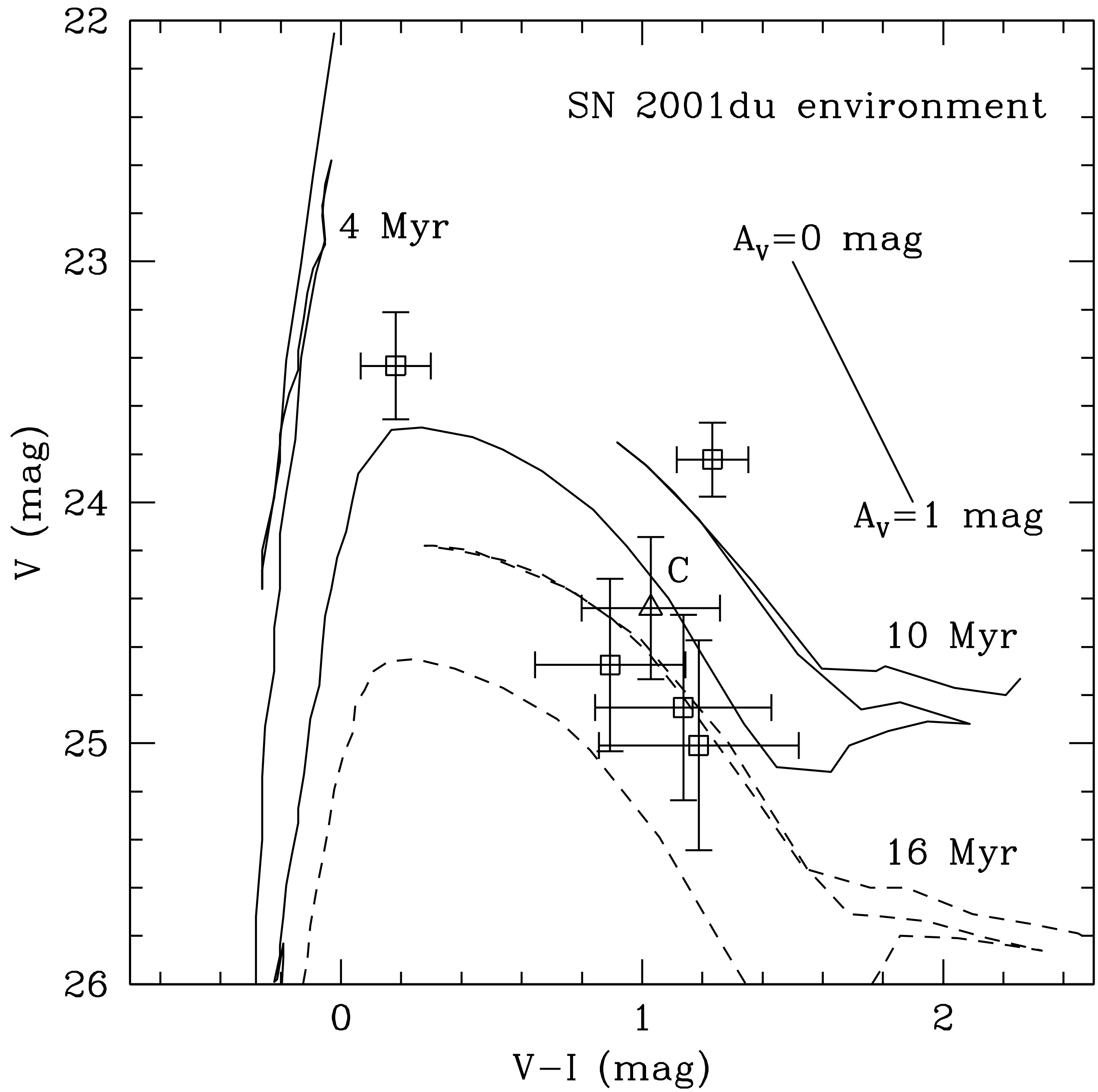

Fig. 22.— The ($V-I$, V) color-magnitude diagram for the SN 2001du environment. The progenitor candidate, Star C (see Figure 20), is represented with an *open triangle*, and other stars with *open squares*. (Stars A and B are not detected at I.) Also shown on the diagram are 4, 10, and 16 Myr isochrones from Bertelli et al. (1994) and the reddening vector, following the Cardelli et al. (1989) reddening law. The isochrones are adjusted for the assumed distance modulus $\mu = 31.3$ mag (Silbermann et al. 1999) and reddened, assuming the Galactic $A_V = 0.07$ mag.

Fig. 23.— The site of SN 2001is in NGC 1961 in an archival 4000-s F547M image from 2001 July 14. The error circle has radius $0\farcs4$. Two candidates for the progenitor of this SN Ib, objects A and B, with $M_V^0 \approx -8.3$ and -8.7 mag, respectively, are indicated with tickmarks.